



Optical back-action on the photothermal relaxation rate

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Photothermal effects can alter the response of an optical cavity, for example, by inducing self-locking behavior or unstable anomalies. The consequences of these effects are often regarded as parasitic and generally cause limited operational performance of the cavity. Despite their importance, however, photothermal parameters are usually hard to characterize precisely. In this work, we use an optical cavity strongly coupled to photothermal effects to experimentally observe an optical back-action on the photothermal relaxation rate. This effect, reminiscent of the radiation-pressure-induced optical spring effect in cavity optomechanical systems, uses optical detuning as a fine control to change the photothermal relaxation process. The photothermal relaxation rate of the system can be accordingly modified by more than an order of magnitude. This approach offers an opportunity to obtain precise *in situ* estimations of the parameters of the cavity in a way that is compatible with a wide range of optical resonator platforms. Through this back-action effect, we are able to determine the natural photothermal relaxation rate and the effective thermal conductivity of cavity mirrors with unprecedented resolution. © 2021 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

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1. INTRODUCTION

Light is a powerful tool in engineering the dynamics of the system with which it interacts. A well-known example is the optical spring [1–8] and damping effects [9–14] observed in optomechanical systems where a mechanical oscillator and an optical cavity are coupled via the radiation pressure force of light. An anti-restoring force and a viscous damping force induced by the radiation pressure force are exhibited in the red-detuned regime where one can exploit the optical damping effect to cool the mechanical oscillator to its ground state [11,15,16]. A blue-detuned laser, on the other hand, produces an optical restoring force as well as an anti-damping force. The restoring force has led to applications in optical trapping and levitation [4,17], while the anti-damping force has a critical role in the arousal of self-sustained oscillations [18,19] and chaotic behaviors [20–22] in the system. The natural relaxation rate of photothermal effects in an optical cavity also has a distinctive dependence on the detuning of the driving field. Even though it develops from a very different dynamical process, this phenomenon has properties similar to the radiation-pressure-induced optical spring. In particular, it can be employed to characterize photothermal parameters in a cavity with unprecedented resolution.

Characterizing the photothermal parameters and dynamics can reveal important information about the system. On one hand, photothermal effects can impose a limit to state-of-the-art displacement measurements of high-sensitivity interferometers

[23–26], from small atomic-force-microscope-cantilever optical cavities [27] to kilometer-scale gravitational-wave detectors such as LIGO [23,28,29]. In extreme applications, the shot noise of the absorbed light can set a fundamental limit on the sensitivity of the measurements [30,31] and the production of low-frequency squeezing [32]. On the other hand, photothermal effects were found to be effective in suppressing the Brownian noise of a mechanical oscillator [33,34] and may even cool a mechanical resonator close to its quantum ground state [35].

Braginsky *et al.* [23] were the first to advance a model for photothermal effects in interferometric systems. Their analysis approximated the targets as half-infinite mirrors and is valid in the so-called adiabatic limit, where the thermal diffusion length is shorter than the beam spot radius. In terms of dynamical photothermal effects, this approximation corresponds to the regime of frequencies higher than a critical cutoff frequency determined by the photothermal relaxation rate. Cerdonio *et al.* proposed a complete model valid over the full dynamical range [31]. This model was soon confirmed experimentally [36] and extended to account for thin-film coatings and higher-frequency corrections [37]. Other recent approaches [38,39], despite being successful at an absolute calibration of the photothermal parameters, often required pump-probe schemes and involved complex fitting models. The photothermal parameters reported by these investigations have a relative uncertainty on the order of ≈ 10 –20%.

In this work, we report for the first time the explicit dependence of the natural relaxation rate of photothermal effects on cavity

detuning, in analogy to how the mechanical frequency of a mirror is modified by the radiation pressure's optical spring effect in optomechanical systems. The back-action of the cavity modifies the relaxation rate to be faster by more than an order of magnitude. This can be crucial in the evaluation as well as in the control of the photothermal response of any cavity-based system and can be applied to build optical filters with a tunable critical cutoff frequency. Awareness of this optical correction is also important when exploring the complex dynamics of a hybrid system, such as optomechanical cavities strongly coupled to photothermal effects [28,40,41].

As a demonstration, we apply this back-action-induced correction to precisely calibrate the photothermal parameters of our system. Unlike previous characterizations, our scheme and model present three unique properties. First, our scheme takes advantage of photothermal self-locking of the cavity and can be performed *in situ* with only a single laser beam, an optical modulator, and two photodetectors, with no need for external feedback control. Second, our method is compatible not only with amplitude modulation but also with phase modulation of the cavity field, generalizing our scheme to a broader set of experiments. Finally, our proposal offers a more concise measurement with only two free parameters, allowing for precise fitting to experimental data. Experimentally, we show that the altered photothermal relaxation rate can be an order of magnitude larger than its natural value. Additionally, the best fit of the cavity phase response gives us the photothermal relaxation rate of 16.2 ± 0.2 Hz, corresponding to the thermal conductivity of 1.182 ± 0.016 W/Km. The precision attained is about an order of magnitude better than previous works [36,38,39].

2. MODELING

We consider an optical cavity driven by an intense laser field that heats the cavity mirrors and produces strong photothermal effects. We start with an empirical model that has been demonstrated [42,43] to describe photothermal interactions. It is assumed that the change in cavity length increases (or decreases) exponentially as the cavity mirrors are heated up by the stationary intracavity optical field. Denoting by q_{th} the total change in the optical path length induced by the net photothermal effects and by a the amplitude of the intracavity field, the dynamics of the photothermal interaction between the two can be modeled by the following two equations of motion, in the frame rotating at the driving laser frequency ω :

$$\dot{q}_{\text{th}} = -\gamma_{\text{th}}(q_{\text{th}} + \beta P_c), \quad (1)$$

$$\dot{a} = -[\kappa/2 - i(\Delta + Gq_{\text{th}})]a + \varepsilon_1 + \varepsilon_0 \cos(\omega t + \varphi), \quad (2)$$

where γ_{th} is the photothermal relaxation rate, β is the photothermal response coefficient, and κ denotes the decay rate of the cavity. The term $-iGq_{\text{th}}a$ in Eq. (2) indicates the interaction between the cavity mode and photothermal displacement by the coupling constant $G = \omega_c/L_c$ (where ω_c is the cavity eigenfrequency, and L_c denotes the natural cavity length). The intracavity power is written explicitly as $P_c = \hbar\omega_c|a|^2/\tau_{\text{cav}} = \hbar Gc|a|^2/2$, with $\tau_{\text{cav}} = 2L_c/c$ being the round-trip time of cavity photons. The cavity is driven at a detuning Δ from resonance, by an optical field of amplitude ε_1 , which is sinusoidally modulated at a frequency ω and phase φ by a percentage $\varepsilon_0/\varepsilon_1 \ll 1$. We consider amplitude modulation

here; however, the method works equally well with phase or frequency modulation (see Supplement 1). Note that the modulation is external and is applied for the purpose of characterizing the photothermal effects.

Since the modulation depth is small, we can assume small deviations from the steady-state solutions and substitute the assumptions $q_{\text{th}} = q_{\text{th}}^0 + \delta q_{\text{th}}$ and $a = a_0 + \delta a$ into Eqs. (1) and (2) to obtain the steady states of the system:

$$0 = q_{\text{th}}^0 + \alpha|a_0|^2, \quad (3)$$

$$0 = -\kappa a_0/2 + i(\Delta a_0 + G a_0 q_{\text{th}}^0) + \varepsilon_1, \quad (4)$$

and the first-order dynamics:

$$\delta \dot{q}_{\text{th}} = -\gamma_{\text{th}} [\delta q_{\text{th}} + \alpha(a_0 \delta a^* + a_0^* \delta a)], \quad (5)$$

$$\begin{aligned} \delta \dot{a} = & -\kappa \delta a/2 + i\Delta_c \delta a + iG a_0 \delta q_{\text{th}} \\ & + \frac{\varepsilon_0}{2} e^{-i(\omega t + \varphi)} + \frac{\varepsilon_0}{2} e^{i(\omega t + \varphi)}, \end{aligned} \quad (6)$$

where $\alpha = \hbar Gc\beta/2$, and $\Delta_c = \Delta + Gq_{\text{th}}^0$. Combining Eqs. (3) and (4) gives us a cubic equation for $|a_0|^2$, implying that the system states can stay in a bistable regime at certain conditions [44,45]. The cavity can be either self-locked or anti-locked depending on the scanning direction of the detuning. For example, consider the case where the photothermal effects manifest by expanding the medium of the cavity, thus lengthening the effective cavity length when power increases ($\beta > 0$). A self-sustained equilibrium can be reached on the red-detuning side of resonance, where less intracavity power would shift the resonance back to lower frequencies and thus increase the power again. In cases where photothermal effects would instead decrease the effective length of the cavity ($\beta < 0$), the self-locking mechanism is triggered on the opposite, blue-detuned side of resonance.

Assuming $\gamma_{\text{th}} \ll \kappa$, we substitute the ansatz, $\delta q_{\text{th}} = Qe^{-i\omega t} + Q^*e^{i\omega t}$ and $\delta a = A_-e^{-i\omega t} + A_+e^{i\omega t}$, into Eqs. (5) and (6) and obtain the solution to the photothermal displacement expanded in the powers of $\frac{\gamma_{\text{th}}}{\kappa/2}$ (see Supplement 1):

$$\begin{aligned} Q = & \frac{\gamma_{\text{th}}\alpha\varepsilon_1\varepsilon_0 e^{-i\varphi}}{(\Delta_c^2 + \kappa^2/4)} \frac{1}{i\omega - \gamma_{\text{th}} + \zeta\gamma_{\text{th}}} \\ & \times \left(1 + \left(\frac{\gamma_{\text{th}}}{\kappa/2} \right) \frac{i\omega}{\gamma_{\text{th}}(\Delta_c^2 + \kappa^2/4)} \frac{i\omega - \gamma_{\text{th}} - \gamma_{\text{th}}\zeta}{i\omega - \gamma_{\text{th}} + \gamma_{\text{th}}\zeta} + \mathcal{O}\left(\frac{\gamma_{\text{th}}}{\kappa/2}\right)^2 \right), \end{aligned} \quad (7)$$

with

$$\zeta = \frac{\sigma v}{(v^2 + 1/4)^2}, \quad (8)$$

where $\sigma = 2\alpha\varepsilon^2 G/\kappa^3$, and $v = \Delta_c/\kappa$. The dimensionless parameter σ is a compound coefficient, linearly proportional to the photothermal coefficient β and inversely proportional to the cavity decay rate κ . It can be considered as an effective photothermal coefficient intrinsic to the full cavity. In particular, we note that characterizing the dependence of ζ on v , one can directly extrapolate the value of σ and therefore the photothermal properties of the system. It is noted that $\zeta < 0$ holds under self-locking conditions: if the photothermal coefficient is positive (i.e., $\beta > 0$), the cavity

can be self-locked only at red detuning (i.e., $\Delta_e < 0$). Similarly, Δ_e is greater than zero when $\beta < 0$. This indicates that $\sigma\nu$ and thus ζ are negative. The calibration of ζ , which we will discuss later, is subject to this property. We now look at the zero-order term of Eq. (7) and define the term $\chi_{th}(\omega) = (i\omega - \gamma_{th} + \zeta\gamma_{th})^{-1}$ to be the photothermal susceptibility, i.e., how the x_{th} degree of freedom responds to an external optical field. The photothermal susceptibility is a single-pole function whose cutoff frequency corresponds, in the absence of photothermal–cavity interaction (i.e., $G = 0$ or $\zeta = 0$), to the natural photothermal relaxation rate γ_{th} . When the photothermal effects are coupled to the intracavity optical field, however, the cutoff frequency of the photothermal responses is modified by

$$\delta\gamma_{th} = -\zeta\gamma_{th}. \quad (9)$$

This optical correction phenomenon presents analogies to the optical spring effect driven by radiation pressure in optomechanical systems where the stiffness and damping rate of the mechanical oscillator are modified when interacting with the cavity field. Here, for the first time, we show that interaction with the cavity also modifies the response rate to photothermal excitations, γ_{th} . We will also show that this effect can be exploited to allow precise characterization of the photothermal parameters of the cavity, with a relative precision that is an order of magnitude better than previous works [31,36,38,39] operating at the cavity resonance where $\delta\gamma_{th} = 0$.

The dominant time-varying signal of the cavity transmission can be normalized as follows by considering the zero-order term of Eq. (7) (see Supplement 1):

$$t_{norm} = \frac{1}{1 + \frac{\zeta}{(i\omega/\gamma_{th} - 1)}}. \quad (10)$$

The amplitude and phase of the transmitted signal are then obtained as

$$|t_{norm}| = \sqrt{\frac{\omega^2 + \gamma_{th}^2}{\omega^2 + \gamma_{th}^2(1 - \zeta)^2}}, \quad \phi = \arctan\left(\frac{-\omega\zeta\gamma_{th}}{\omega^2 + (1 - \zeta)\gamma_{th}^2}\right). \quad (11)$$

These quantities can be observed experimentally at different modulation frequencies to characterize the photothermal parameters. At low modulation frequencies (i.e., $\omega \ll \gamma_{th}$), the amplitude and phase are predicted to be $|t_{norm}| = 1/|1 - \zeta|$ and $\phi = 0$, respectively. At $\omega \gg \gamma_{th}$, the amplitude approximates to one, while the phase change relative to the reference modulation tends again to zero. This predicts that one can observe noticeable phase change only for median modulation frequencies. We also note that, replacing the amplitude modulation with a frequency modulation of the driving signal, the resulting formula for the transmitted signal is functionally identical (see Supplement 1). This indicates that one can use either amplitude or phase/frequency modulation to extract the photothermal parameters with the same model. It is worth noting that one can obtain the photothermal relaxation rate γ_{th} without any knowledge of other cavity parameters. However, more specific knowledge of the system is required to extract the photothermal coefficient β from Eq. (8).

3. EXPERIMENTAL SETUP

The proposed scheme for exploring the photothermal effects is shown in Fig. 1(a). The optical cavity, enclosed within a

transparent box, is the element to be characterized. The Fabry–Perot resonator represented in the figure can be replaced by any other type of optical resonator without loss of generality. The input laser is sent through a modulator before acting as the input to the cavity. We will consider amplitude modulation of the laser beam by an acousto-optic modulator (AOM), even though it is worth reminding that our characterization of the photothermal parameters can also be performed with phase or frequency modulation. A low-reflectivity beam splitter following the AOM is used to pick up a reference signal. We scan the modulation frequency and vary the effective cavity detuning to collect data from two detectors, one (red detector) as a reference tapped off the driving input, and the other (blue detector) on transmission encoding the photothermal response of the cavity. We obtain the phase response of the cavity by comparing the relative phase difference between the reference and transmitted signals.

We experimentally observe the optical correction to the photothermal relaxation rate using a concave–convex Fabry–Perot cavity, as shown in Fig. 1(b) with a finesse of 5700 and a decay rate of 520 kHz. The power of the cavity input laser is set as 100 mW. The setup is in room-temperature and ambient-pressure conditions, and is built using an Invar spacer to reduce the effect of stochastic thermal fluctuations. Both cavity mirrors are fused-silica substrates with ion-beam sputter coating for high reflectivity at our operating wavelength of 1064 nm. The coating has an optical

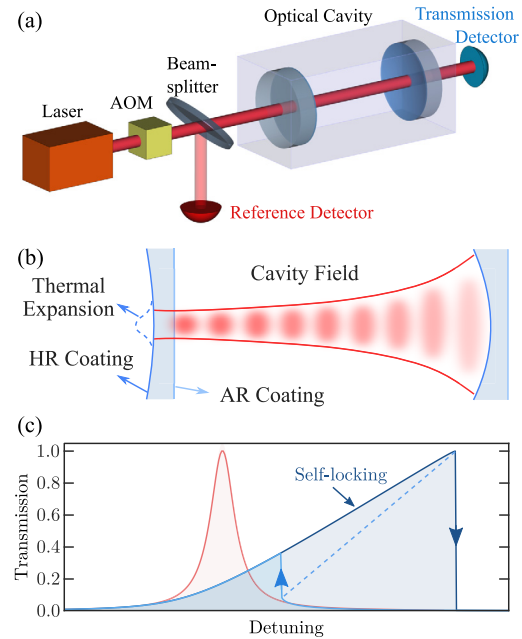


Fig. 1. (a) Setup. The system enclosed with the blue box is the (generic) cavity to characterize. A low-reflectivity beam splitter is used to pick up the reference beam before the laser is injected into the system. The input laser power is slightly modulated using an acousto-optic modulator (AOM). The powers of the reference beam and transmitted beam are detected by two photodiodes. (b) Schematic of the concave–convex optical cavity used for experiment. The substrate of one of the cavity mirrors is placed inside the cavity to enhance the photothermal effects. (c) Diagram of system bistability. The red profile shows the typical Lorentzian response of an optical cavity as a function of detuning. In blue, the response of a similar cavity is modified by photothermal interaction. At high intracavity powers, the system can evolve into the bistable regime where the cavity behavior depends on the scan direction, which drags or skips through resonance depending on the scan direction.

absorption of less than 10 ppm, offering very small susceptibility to photothermal effects. The substrate of the front mirror is placed inside the cavity so as to enhance the photothermal effects [Fig. 1(b)] [45]. The mirror coatings expand outwardly, and the refractive index of the substrate changes when the cavity mirrors are heated by the intracavity optical field. Several photothermal effects are present in the system (see Supplement 1 for further discussion). Here we look at their net contributions and assume that different photothermal effects collectively change the cavity response in the same way, either because only one is dominant or because they all cooperate with similar time constants. This approach allows us to measure the effective photothermal parameters that are crucial for the characterization and analysis of the cavity photothermal response.

The bistable response occurring in these conditions is represented in Fig. 1(c), which shows the cavity response obtained under strong photothermal interaction as follows from Eqs. (3) and (4). The typical Lorentzian response of an optical cavity is deformed, and because of the sign of the interaction, the cavity will self-stabilize when in the red-detuning regime [44,46]. We employ this behavior to explore the system dynamics without the need for any external active feedback control.

We show the measured phase response of the cavity transmission in Fig. 2(a) for two different detunings, $\Delta_c/\kappa = 0.38$ (blue) and $\Delta_c/\kappa = 0.53$ (red). The data (circles) are fitted according to Eq. (11) using nonlinear regression. The experimental data are in excellent agreement with the model. The values of $\gamma_{th}/2\pi$ obtained from the best fit at these two different detunings are rather close, i.e., 16.3 ± 0.2 Hz and 16.0 ± 0.2 Hz, respectively. The values of the other free parameter ζ are -25.5 ± 0.2 for $\Delta_c/\kappa = 0.38$ and -19.2 ± 0.2 for $\Delta_c/\kappa = 0.53$. The errors given here indicate the 95% confidence interval of the nonlinear regression. We apply a nonlinear transformation (see Supplement 1) to the data to achieve linearity, as shown in the insets of Fig. 2(a). The weighted linear fitting of the transformed data gives results compatible to the nonlinear regression. We substitute the value of γ_{th} and ζ obtained from the best nonlinear fit of phase into Eq. (11) to get the theoretical estimation of the amplitude, indicated by the solid lines in Fig. 2(b). We can also see a good agreement between the data

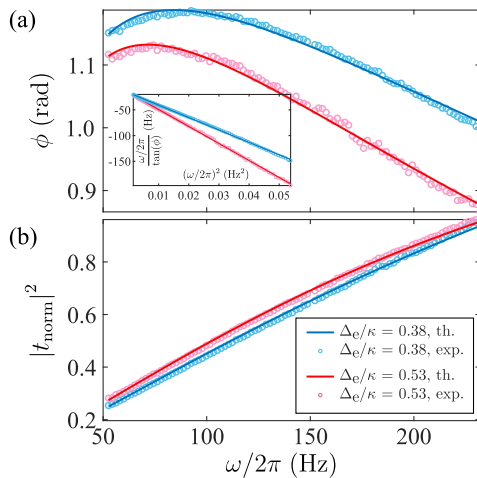


Fig. 2. (a) Phase response of the cavity as a function of modulation frequency (dots) and corresponding nonlinear fitting (solid lines). A nonlinear transformation of the data is performed to achieve linearity, as shown in the insets. (b) We put the parameters obtained from the fitting of phase into the amplitude response. We still find a good agreement between the theory and experiment.

and the model. We note that the amplitude of the transmission is nonlinearly dependent on the modulation frequency, as shown in Eq. (11), even though the dependence looks linear in Fig. 2(b) in the given frequency range. This frequency range is chosen such that the measured phase is more sensitive to frequency change and thus provides smaller uncertainty for the fitting process.

In principle, both the amplitude and phase signals are suitable candidates for fitting the photothermal response. In practice, however, the amplitude parameter requires a normalization process that involves the calibration of ε_l , ε_0 , Δ_c , and κ , or equivalently, just an overall normalization factor N (see Supplement 1). Thus, fitting for amplitude adds a layer of complexity that can be readily avoided by considering the phase parameter instead. In Fig. 2, the traces of amplitude obtained at two detunings are rather close, while the two plots for the phase are distinctive, confirming that phase fitting is a better candidate to process and extract the photothermal parameters.

4. RESULTS

A. Optical Correction of the Photothermal Relaxation Rate

Recalling Eq. (9), the optical correction effect is manifested in the dimensionless quantity ζ , which can be characterized by fitting the data of cavity transmission into Eq. (11). Figure 3(a) presents the nonlinear dependence of $\delta\gamma_{th}/\gamma_{th}$ (i.e., $\delta\gamma_{th}/\gamma_{th} = -\zeta$) on the normalized detuning Δ_c/κ . The results show that the modification of γ_{th} in the presence of the cavity field can be tens of times larger than its natural value. This detuning-dependent feature of the photothermal response can be crucial in exploring the dynamics of a cavity-based system. For example, the natural photothermal relaxation rate is generally slower than the mechanical response in many optomechanical systems. At specific parameter regimes, however, the photothermal spring can speed up the photothermal effects' excitation to the point where the mechanical and photothermal response rates are comparable.

A straightforward application of the optical correction effect is the precise characterization of photothermal parameters. Generally, the photothermal response is relatively slow, and thus its characterization is performed at the low-frequency regime where the data collected are more susceptible to environmental noise and may be limited by the integration time. The cavity-induced optical correction, however, allows us to characterize the photothermal parameters at modulation frequencies much higher than γ_{th} to reach high precision. The agreement between data and experiment presented in Fig. 3(a) is an indication of the potential precision of this technique.

B. Precision of Characterization

Our scheme allows us to estimate the value of the photothermal coefficient. As suggested by Eq. (8), the parameter ζ varies only as a function of the normalized detuning $\nu = \Delta_c/\kappa$. With the data presented in Fig. 3(a), we employ this feature to do a linear fitting in terms of $\frac{\nu}{(\nu^2 + 1/4)^{3/2}}$ to obtain the effective cavity photothermal coefficient σ . The data and their best fit correspond to a coefficient $\sigma = -10.2 \pm 0.4$. The negative value of σ , which is proportional to the photothermal coefficient β , indicates that the effective optical path length of the cavity increases when the optical field heats the cavity mirrors.

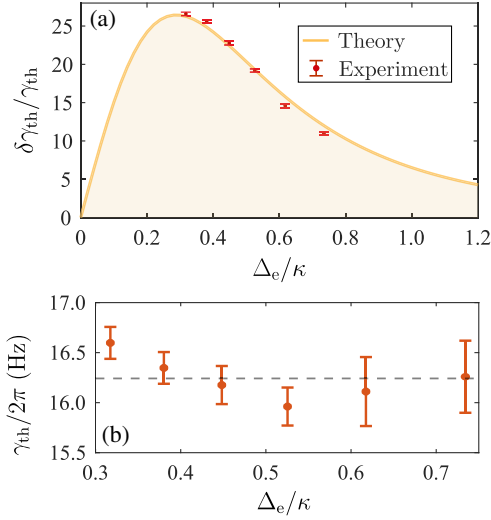


Fig. 3. (a) Optical correction of photothermal relaxation rate as a function of effective cavity detuning. The optical correction of the natural photothermal relaxation rate is shown to be nonlinearly dependent on the cavity detuning. The dots with error bars are the experiment results, and the solid line presents the theoretical inference. (b) Photothermal relaxation rate γ_{th} characterized at different detunings. The error bars indicate the 95% confidence bounds of the fitting. The dashed line is the mean value of the measurements. These measurements give us $\gamma_{th}/2\pi = 16.2 \pm 0.2$ Hz, where the error is the standard deviation of multiple measurements.

In addition, the fitting values of γ_{th} at different detunings are given in Fig. 3(b). These measurements give an average photothermal relaxation rate $\gamma_{th}/2\pi = 16.2 \pm 0.2$ Hz. The error is the standard deviation over multiple measurements. To compare the measurement precision of photothermal parameters with previous works [36,38,39], we can infer the effective thermal conductivity using $\kappa_{th} = \gamma_{th}\rho Cr_0^2$ [31]. Here r_0 is the beam radius at the front mirror where the photothermal effects are dominant, and C and ρ are, respectively, the specific heat capacity and the density of fused silica. Using the room-temperature values of $C = 6.7 \times 10^2$ J kg K and $\rho = 2.2 \times 10^3$ kg/m³, and inferring the beam radius to be $r_0 = 50/\sqrt{2}$ μ m from the cavity geometry, we obtain the effective thermal conductivity value of $\kappa_{th} = 1.182 \pm 0.016$ W/Km. Two

unique features allow for greater precision: the reduced number of free parameters in our model and the ability to modulate the laser power at frequencies higher than γ_{th} due to the off-resonance optical correction.

C. Full-System Dynamics

Figure 4 displays the full response of the system, comparing experimental data (left panels) to theoretical results (right panels). With regard to the theoretical plots, we used the values obtained from the fits in Fig. 2. There is a good agreement between the experiment and theory. Figures 4(a) and 4(b) show that the cavity acts as a high-pass filter with cutoff frequency tuned by the cavity detuning. In other words, the cavity allows only a high-frequency modulated signal to go through. This is due to the low-pass property of the photothermal effects. At low modulation frequencies, the power fluctuation of the intracavity field can be suppressed by the photothermal back-action. The photothermal effects, however, fail to catch up with the fast response of the cavity field at high-frequency modulations. The natural photothermal relaxation can be modified by the cavity's back-action to induce a higher cutoff frequency. Cavity power and detuning, therefore, coordinate the effective high-pass filter response of the cavity. It is noted that the full high-pass filter is not single-pole as suggested by Eq. (11), and its bandwidth might also be subject to Cerdonio's theory [31]. In Figs. 4(c) and 4(d), we show that the phase change of the laser going through the cavity due to photothermal effects peaks at a small detuning of about 0.3κ and a modulation frequency of about 90 Hz.

5. CONCLUSION

We observe that the natural photothermal relaxation rate can be altered in the presence of photothermal–cavity interaction. This feature, analogous to the optical spring effect, can be crucial in analyzing the photothermal dynamics in a cavity-based system and indicates a way of building optical filters with a tunable critical cutoff frequency. Also, we report a convenient technique for precisely characterizing photothermal parameters *in situ* by employing the optical correction effect. Our model shows that one can modulate either the power of the optical input field or the

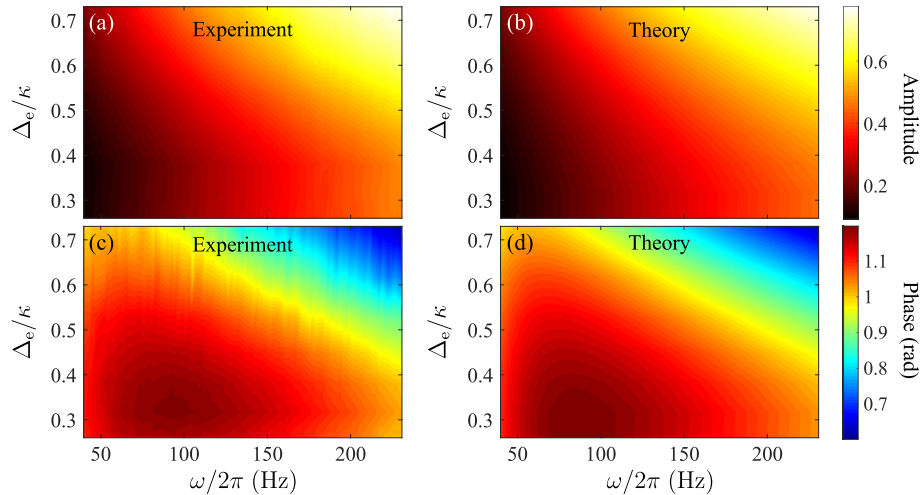


Fig. 4. (a), (b) Amplitude responses as a function of modulation frequency ω and effective cavity detuning $v = \Delta_e/\kappa$. The bandwidth of the photothermal effects increases as the cavity is set close to its resonance. (c), (d) Phase responses of the cavity.

cavity detuning to achieve the characterization of photothermal effects. Experimentally, the measured amplitude and phase of the cavity transmission agree excellently with the theoretical model. The best fit of the phase response gives the photothermal relation rate of 16.2 ± 0.2 Hz. This characterization is an order of magnitude more precise than previous works. It is worth noting that the natural photothermal relaxation rate of a cavity mirror depends on the laser power density, and the photothermal coefficient is determined mainly by the absorption in the mirror coatings. Appropriate engineering of the mirror coating, substrate material, or cavity geometry, therefore, can allow us to observe photothermal optical correction at relatively low laser powers.

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Supplemental document. See Supplement 1 for supporting content.

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